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PROCEEDINGS

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Environmental and Material Composition Effects on Film Permeability as Related to Meat Packaging

Seymour G. Gilbert*
Grace R. Huang-Lai
Christopher C. Lai

Introduction

The selection of a plastic film for packaging is often based on many factors. An overriding consideration for a foodstuff is the permeability of the package walls to various penetrants. The penetrants of major importance are moisture, oxygen and, in certain cases, carbon dioxide. Other substances, including organic vapors and aromas, are often important, depending on both the product and its environment during the span of its use.

Knowledge of the barrier properties of the film is essential in successful design of packaging to extend the product storage life. Different products have different film permeability requirements. In general, there are two types of packaged foods. First is the packaged non-living materials in which the useful storage period is governed by the degree of effectiveness of the package as a barrier to a particular penetrant or penetrants (Gilbert and Hayakawa, 1975). The second type is packaging of a living system, such as fresh meat or produce. These products have a number of complicating factors which are not present in the preceding case (Daun and Gilbert, 1974, 1979). A certain composition of gas and vapor is required in the package to maintain the desirable biological/biochemical activities of the system. Thus, proper film selection and optimizing package design are important in controlling product quality changes, such as color, aroma, texture, microbial growth, etc. Henig and Gilbert (1975) used computer-aided mathematical solutions to determine the equilibrium concentration of gases within a packaged produce and the time necessary to reach this condition. The technique could also be applied to package design for any commodity.

An understanding of the factors affecting film permeation would be desirable in package film selection and design of packaged product environment. In this presentation, we will first review the theory of permeation and various factors that affect film permeability. Then packaging requirements in terms of barrier properties for meat products will be presented.

Theory of Permeation

The rate of permeation is defined as the amount of material passing through a membrane or film per unit of time.

*S. G. Gilbert, Department of Food Science, Cook College New Jersey Agricultural Experiment Station, Rutgers University, New Brunswick, New Jersey 08903

The permeation rate of gas or vapor through a package is highly dependent on the package film composition, nature of the gas and the environment. Movement of small molecules through the polymeric systems may occur by at least three processes: (a) Activated diffusion of molecules through homogeneous amorphous material, (b) Flow through a discontinuity (pore or crack) in the material, or through faulty seal or seam, (c) Combination of the above two processes.

Activated Diffusion

The activated diffusion process can be generally characterized by three steps. First, penetrant dissolving at one side of the film. Then it diffuses through the film under a concentration gradient. Finally, the penetrant evaporates from the other, lower-concentration, surface. Both first and third steps depend primarily on the solubility of the penetrant in the polymer, whereas the second step is diffusion dependent. The higher the solubility of diffusion rate, the more likelihood of greater movement of a gas or vapor.

For the steady-state activated diffusion process, the rate of mass flux of gas may be expressed by Fick's first law of diffusion:

$$q = -D\frac{dC}{dx} \qquad (1)$$

where:

q = rate of diffusion per unit area of film in unit time
D = diffusion coefficient
C = concentration
x = distance diffused at concentation C

If D is independent of the concentration or location in the film, the above equation (1) may be integrated between the two concentrations, C_1 and C_2 to

$$q = D(C_1 - C_2)/1 \qquad (2)$$

where:

C_1 and C_2 = steady state concentrations of gas at both surfaces of the film
1 = film thickness

The gas concentrations of penetrant at both surfaces can be related to their partial pressure by means of Henry's law

$$C = Sp \qquad (3)$$

where:

S = solubility coefficient of the penetrant in the polymer
p = gas or vapor partial pressure

48

substitution of Sp for C in equation (2) gives

$$q = DS(p_1 - p_2)/1 = P(p_1 - p_2)/1 \qquad (4)$$

or $\quad P = DS = q1/(p_1 - p_2) \qquad (5)$

The product DS has been defined as the permeability constant or permeability coefficient. This value is a constant at a given temperature when Henry's law is obeyed and that D is independent of penetrant concentration. When Henry's law is not obeyed, or the diffusion is concentration dependent, a non-linear pressure gradient usually exists. An example is the dual mode sorption mechanism of Vieth and Sladek (1965).

Flow Through Pores

Penetrant size relative to pore or capillary and the viscosity of the penetrant are the governing factors of mass flux through the nonhomogeneous film. In the case of streamline flow of a single-component through capillaries, Poiseuille's law can be used.

$$q = \frac{\pi r^4}{8\mu L}(p_1 - p_2) \qquad (6)$$

where:

r = radius of capillary
η = viscosity of the penetrant
L = length of capillary

For cases conforming to Poiseuille's law, the permeability coefficient varies inversely proportional to the penetrant viscosity, which increases with temperature (Hall, 1973). That is, P decreases with increase in temperature for large capillaries.

When the diameter of the pore is less than the mean free path of the gas molecules, the flow rate becomes independent of pressure and pore diameter. The flow can be described by Knudsen's law.

$$q = \frac{4r^3}{3L} \cdot \frac{(2\pi M)^{1/2}}{RT}(p_1 - p_2) \qquad (7)$$

where:

M = molecular weight of penetrant
R = gas constant
T = absolute temperature

The flow, following Knudsen's law, is independent of penetrant viscosity and P decreases with temperature. This is in contrast with permeability governed by activated diffusion, where the mass flow rate increases exponentially with temperature.

Simultaneous Diffusion and Flow Through Pores

Frisch (1956) derived an equation for combined diffusion and convection through polymer films possessing pores. At steady state gas flux, where D is assumed constant and local solution equilibrium is attained at the walls of the pores, q is given by:

$$q = D\frac{d}{dx}\left(\frac{C}{1+\phi}\right) + \left(\frac{C}{1+\phi}\right)v \qquad (8)$$

$$\phi = 1/SRTg \qquad (9)$$

where:

v = convective velocity
S = overall solubility coefficient
g = constant factor which is inversely proportional to the total pore volume

Common units used for permeability constant are: $CC(STP) \cdot mil/m^2/24hr/atm$; $CC(STP) \cdot mil/100in^2/24hr/atm$; $CC(STP) \cdot cm/cm^2/sec/cmHg$ and $gm/m^2/24hr/atm$. When comparing permeability constants, one should be very careful to note the units used, or else one material might be mistakenly assumed to be a better barrier than another, while in reality that is not the case.

In addition, there is a common misconception among people regarding a film, like polyethylene, as having a high gas permeation rate relative to water vapor permeability (Gilbert, 1981). This notion probably arises from the usual unit used for the permeability constants: water being in grams, and gases like oxygen in cc. At equivalent gauge, area and time, these two quantities are related by a factor of 24,400/18 or 1,244/1. The driving forces are also not equal. Thus, the normalizing factor for water vapor transmission in the standard transfer units is about 4×10^4 for water to that for a fixed gas.

Factors Affecting Film Permeability

The rate of gas or vapor permeation through a polymeric film depends on a number of parameters.

Nature of Penetrant

Diffusion coefficient and permeation rate are decreased as the size and shape of penetrant molecules increases. The shape factor is especially important as in the case of organic molecules. For branched or cyclic penetrant, the diffusivity is much lower than their linear counterparts of the same molecular weight.

In most cases the permeability of polymers to penetrant increases with similarity of structure, the well known principle of "like dissolves like," and ease with which the penetrant can condense on the barrier material. For example, water vapor has a very low solubility value in hydrophobic polymers, such as polyethylene. As a result, water vapor permeability through polyethylene is much lower than through the hydrophilic materials, such as the cellulosics and nylons. However, the water vapor permeation rate through polyethylene is higher than that of oxygen which has about the same molecular size because of the difference in liquifaction temperature.

The permeation process of organic vapors is quite complex due to the pressure-dependent solubility and the concentration-dependent diffusion coefficient. The solubility of organic vapors does not follow Henry's law. In addition to being penetrants, these vapors behave as solvents or plasticizers which swell the polymer and lead to increased polymer chains and penetrant mobilities. It should be noted that since the solvent-film interaction varies with each polymer, comparison of organic vapor permeabilities cannot be made in a similar fashion as is possible for gases and water vapor.

36th Reciprocal Meat Conference

49

In general, mixtures of gases have no interaction on their film barrier properties. The gases permeate independently according to the partial pressure of each gas. On the other hand, the effect of mixed vapors depends entirely on the individual penetrant's behavior toward the polymer. Complex situations could occur when mixtures contain at least one penetrant that swells the polymer. Swelling due to the water or organic vapor increases the flux of other penetrants. Effect of swelling due to water sorption depends on relative humidity and not on the percent of water vapor in the gas. The presence of water vapor also has an accelerating effect on diffusion of organic vapors in polymers such as polyvinyl acetate and cellulose acetate (Long and Thompson, 1954).

The effect of relative humidity on oxygen permeation of various common films is shown in Figure 1. Hydrophobic polymers give a relative constant rate of permeation all through the range of relative humidity, whereas the hydrophilic materials show a rapid increase of gas flow at higher relative humidity. These curves, which refer to material approximately 0.001 in. thick, are based partly on data given in the literature and partly on practical observations on a limited number of samples in our laboratory. They indicate only the probable order of magnitude and not the specific performance which can be expected from materials from different sources of supply.
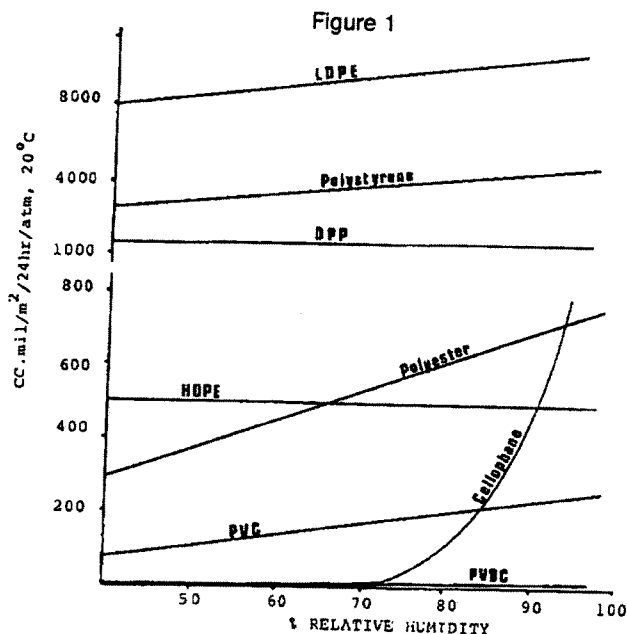

Figure 1

Figure 1. Effect of %rh on O_2 permeability of various films.

Temperatures

The temperature relationship to diffusion and solubility over a small range of temperature can be represented by Arrhenius type relation if the penetrant does not swell the polymer.

$$S = S_0 \exp(-H_s/RT) \qquad (10)$$

$$D = D_0 \exp(-E_D/RT) \qquad (11)$$

where H_s and E_D are apparent heat of solution and activation energy for the diffusion process, respectively, and the subscript zero refers to a standard state. Consequently, from the definition $P = DS$, the temperature dependence of the permeability constant is as follows:

$$P = P_0 \exp(-E_p/RT) \qquad (12)$$

where:

$$E_P = H_s + E_D \qquad (13)$$

E_p is the activation energy for the overall permeation process, and H_s can be expressed as sum of the heat of condensation and the heat of mixing.

$$H_s = H_{cond} + H_{mix} \qquad (14)$$

As the temperature increases, the value of diffusion coefficient increases, and solubility decreases or increases depending on whether H_s is determined largely by H_{cond} or H_{mix}. The dependence of solubility on temperature, however, is small in comparison with that of diffusion coefficient. Therefore, the overall E_p is positive and permeation increases with an increase in temperature.

The overall activation energies of numerous penetrant/barrier systems have been reported in the literature (Crank and Park, 1968; Meares, 1965; Yasuda and Stannett, 1964). These values may be used to calculate the permeabilities at other temperatures using the following relationship (Yasuda and Stannett, 1964):

$$\log P_2 = \log P_1 + \frac{1000E_P}{4.6} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \qquad (15)$$

where P_1 and P_2 are the permeability coefficients at temperatures T_1 and T_2 respectively.

Light and Irradiation

Light usually does not affect the barrier properties of film. There has been considerable activity in recent years in the sterilization of already packed foods by irradiation through the package. The effect of β or γ irradiation of a polymer on solubility and diffusivity depends primarily on the crosslinking to scission ratio (Rogers, 1964). The magnitude of the observed effects generally increases proportionally with the dose.

Film Thickness

The rate of permeation is always inversely proportional to the film thickness if equilibrium conditions have been established. In the case of pre-equilibrium, thickness of polymer improves its barrier properties much more than it does after reaching equilibrium, since the time needed to reach equilibrium is roughly proportional to the square of the thickness if Fick's and Henry's laws are obeyed (Lebovits, 1966).

Nature of Barrier Material

A number of film properties have an effect on the rate of permeation. Since penetrant-polymer interaction has considerable influence on the film permeability, the following material factors should be interpreted as only a general trend.

Structural modifications of polymer usually changes the diffusion and permeability coefficient. These are attributed to alterations of the chain mobility, cohesive energy, and hole volume or "looseness" of the polymer structure. Thus, any increasing quantities such as density, degree of crystallinity,

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50

orientation, cross-linking, saturation, length or polarity of side groups, as well as additives such as plasticizers and fillers in a polymer molecule, will generally reduce the permeability. For example, in our studies on the effect of cross-linking on the permeability of collagen (Lieberman and Gilbert, 1973), data show that both the permeability and diffusion coefficients decrease with increasing degree of cross-linking (Table 1). When the chain segments are tied together at intervals by cross links, the probability of the polymer chains moving away from the same central point and forming a hole for passage of the penetrant will decrease. The same considerations probably apply to inter-molecular "cross linkages" involved in crystalline structures.

Composite Film

Composite structures, including laminations and coated materials, are often used to provide a definite function, such as heat sealability, structural and barrier characteristics, etc. It is usually impractical and uneconomical to reduce permeability by increasing the thickness of one material. Consequently, a more practical way of obtaining the desired permeability and possess other functional requirements is by coating or lamination of the film with one or more other materials of better barrier properties. Table 2 demonstrated

Table 1. Oxygen Permeability of Formaldehyde Cross-Linked Collagen Films

Molecular Weight Between Cross-Links	$P \times 10^{13}(cc \cdot cm/cm^2/sec/cmHg)$	
	86.5%RH	91.0%RH
6100	1109	1301
4300	1277	1348
3400	1480	1636
2700	1648	1816

Ref. Lieberman and Gilbert, 1973

Table 2. Permeability (P) for Selected Plastic Films

Film	Oxygen[a]		Water Vapor[b]	
	U	F	U	F
Polypropylene	889	1152	0.22	0.30
Foam PP	2529	6660	0.56	1.52
Foam PP/PVDC Coated One side	456	2153	0.02	1.09
PP/PVDC/PVDC/PP Lamination	92	819	0.02	0.13
PE/NYLON/PE Co-Extrusion	174	230	0.94	1.13

[a]CC/m²/24hr/atm at 23°C   (Gilbert and Lai, 1982)
[b]gm/m²/24hr at 23°C, 90%RH
U = flat unflexed sheet
F = film partial flexed 20 cycles
    (ASTM method F-392-74)

the effect of PVDC coating and laminate on permeation. The permeation rate for composite film is independent of the order in which the layers are assembled, if D for each layer is constant. In steady-state, the overall permeation coefficient of flow through a barrier of total thickness of 1 composed of n layers is given by

$$\frac{1}{P} = \sum_{i=1}^{n} \frac{X_i}{1} \cdot \frac{1}{P_i} \qquad (16)$$

where: X_i = thickness of the ith layer
P_i = individual permeability coefficient of the ith layer, independent of pressure and concentration.

However, if one of the layers would interact with the penetrant, then the rate through the composite will be dependent on the direction of flow. For instance, while packaging liquid flavor concentrate with PVDC coated polyethylene, it was found that the film with coated side toward the product had a better barrier against flavor loss than if it was packaged in reverse (Talwar et al., 1973).

The co-extrusion technology has great impact on the making of flexible packaging materials in the areas of performance and flexibility of composite webs. Combinations of materials can be simultaneously extruded through a die by the co-extrusion process to achieve structures that provide high performance at reasonable costs. Since it is a one-step process and solvent-free, co-extrusion offers additional potential economic and environmental advantages as compared with the laminating and coating operations. High barrier co-extruded films have been designed for use in packaging snacks and other foods. These films can be designed with hydrophobic exterior polymers with high barrier but water-sensitive cores, such as ethylene vinyl alcohol. Table 2 illustrates one possible combination.

Mechanical Damage

In practical situations, barrier materials are often creased and subjected to other adverse effects as a result of flexing that occurs during machining and handling of the film and finished package. These abuses can lead to increases in gas or vapor permeability due to structural damage of the polymeric film.

A Gelbo Flex tester was used to simulate the package abuse (Gilbert et al., 1983). Numerous pinholes could be seen by naked eyes on flexed glassine. On the other hand, flexed PE/NYLON/PE co-extruded was only wrinkled without visible pinholes. Among all the flexed films studied, nylon extrusion gave the best resistance to mechanical damage and barrier against organic vapors. Effect of flexing on oxygen and water vapor transmission of selected plastic films are also presented in Table 2. It can be seen that flex damage is a function of nature of the film, coating, laminate or co-extrusion.

Barrier Requirements for Packaged Meats

The preceding discussion has considered the mechanisms and factors affecting film permeation. Combining this information and understanding the micro-environment of the product, one should be able to select and design optimum

packaging materials in terms of barrier properties for packaged meat and meat products.

The science and technology of meat packaging have been reviewed by many authors (Mills and Urbin, 1960; Brody, 1970; Sacharow and Griffin, 1970; Daun and Gilbert, 1979; Rizvi, 1981). In the following, we shall examine how permeation relates to quality of packaged meats. Some unpublished data from our research will be presented.

Fresh Meats

There are two conflicting conditions for packaging of fresh meats. Oxygen permeable film is required to maintain the desirable red oxymyoglobin pigment. On the other hand, a relatively gas impermeable film is needed to minimize microbial growth. The chemistry of meat pigments has been discussed by Fox (1966). Landrock and Wallace (1955) studied the role of film oxygen permeability to fresh red meat color. They found that the minimum oxygen permeability requirement is about 5,000 ml/m^2 · 24 hr · atm at 75°F. This requirement has been shown by Daun et al. (1971) to be fortuitous as it is determined largely by the oxygen demand of the indigenous microflora and not the meat pigment. A review of the relationships of microflora to packaged meats was given by Ingram (1962). The storage life of the vacuum packaged meat, as assessed by discoloration and development of putrefactive odors, was shown by Newton and Rigg (1979) to be inversely related to film oxygen permeability in keeping with the principle that microbial growth is the key relation to O_2.

In practice, a film highly permeable to oxygen is used for packaging fresh meats to be stored only 2 or 3 days. Rizvi (1981) listed the film oxygen permeability requirements for various meat packaging (Table 3) without consideration to the microbial factor. Other requirements are low water vapor permeation rate, impermeability to foreign odors and several physical properties including flexibility, clarity, high wet strength, nontoxic, grease proof and durability at low temperatures.

Fresh meats could have a much longer storage life if they were vacuum packaged in oxygen and water vapor impermeable film. However, the anaerobic condition causes the formation of purplish red color of reduced myoglobin. In one of our studies, we monitored the color changes of vacuum packaged meats with time (Gilbert et al., 1981). One group of beef chunk steaks was vacuum packed (Group-V) in PE and

PP laminated pouches, while another group was packed with about 100 cc of air in the headspace of the pouches (Group-A). One half of each group was kept under fluorescent light and the other half was stored in darkness at 3°C environment. Changes in meat surface color were measured with a Hunter Color Meter (D25P-2).

Both oxygen and carbon dioxide permeabilities of the pouch material were determined, and their values were 1273 and 7036 cc/m^2/24hr/atm at 23°C, respectively. The oxygen permeation rate is higher than the recommended rate for vacuum packaged fresh meat as listed in Table 3. However, it is well below the value suggested for fresh retail cuts.

The color of meat for all packages turned brownish in two days. No color differences were observed between packages stored under fluorescent light and those kept in darkness. Changes in the loss of red color (Δa) and loss of brightness (ΔL) are shown in Figures 2 and 3, respectively. Gas composition within the package was determined using the gas
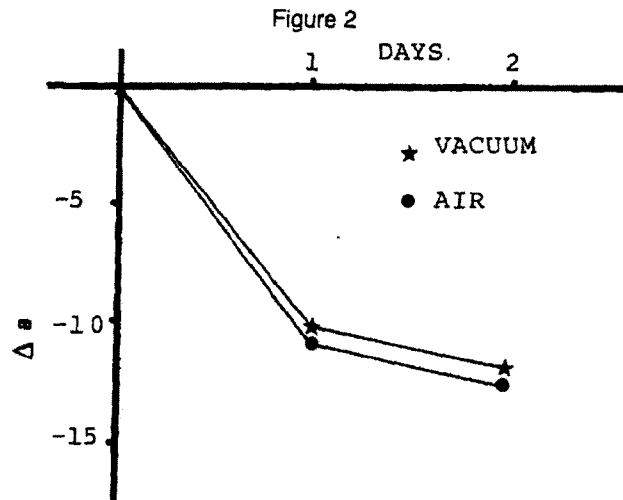
Figure 2. Changes in loss of redness (Δa) of packaged fresh beef samples.
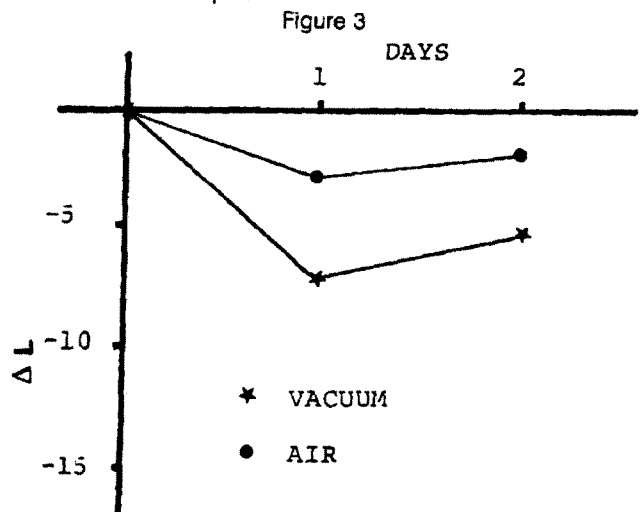
Figure 3. Changes in loss of brightness (ΔL) of packaged fresh beef samples.

Table 3.   Film O₂ Permeability Requirement for Meat Packaging

Product	P	Comments
Fresh Retail Cuts	5000	Oxygenation of Myoglobin Meat Blooms
Vacuum Packaged Fresh Meat	40	Retards Myoglobin Conversion to Metmyoglobin
Cured Meat	100	Retards Degradation of Nitric Oxide Myoglobin
Vacuum Packaged Processed Meat	15	Minimum Degradation of Nitric Oxide Myoglobin

P = CC/m²/24hr/atm at 23°C   (Rizvi, 1981)

52

chromatographic technique. Gradual increase of CO_2 was found for both groups with substantial decrease in headspace oxygen of Group-A. It was suspected that the color changes were due to the oxidizing of myoglobin to metmyoglobin by microbial metabolites. Group-V showed relatively low microbial activities, due to lack of oxygen inside the packages. However, sufficient oxygen might be present in the meat surface fluid to allow microbial metabolites to form, which changed the meat to the undesirable brownish color.

Gilbert et al. (1981) further investigated the effect of initial bacterial load on the color stability of packaged meat. Two meat samples, Meat-Hi and Meat-Low, with initial bacterial load of 2.5×10^4 and 2×10^2 count/cm^2, respectively, were vacuum-packaged with the PE/PP laminated pouches. Both samples were stored at 3°C in darkness.

Figure 4 shows the redness changes of both packaged meats. An arbitrary interpretation of visual color acceptability in terms of redness (a value) was used according to Rickert et al. (1957). Meat-Hi with higher initial bacterial load started to turn brown after 3 days of storage, whereas Meat-Low with low initial bacterial load maintained redness in the satisfactory region after 7 days of storage. The bacterial loads after 7 days were 3×10^5 and 7×10^3 counts/cm^2 for Meat-Hi and Meat-Low, respectively.

The results show that it is possible to maintain an acceptable red meat color up to a week with an intermediate oxygen permeability material under the condition which avoids an undue initial load of microorganisms and at low temperature restriction growth. It is concluded that much of the literature concerning permeability requirements of fresh meat is not valid for commercial meats when the relation to microbial competition for oxygen is not considered. Gilbert and Daun (1971) had previously demonstrated that true oxygen demand by sterile excised meat discs for maintaining redness color is quite low, whereas higher demands reflected the microbial status of the meat under specific test conditions.
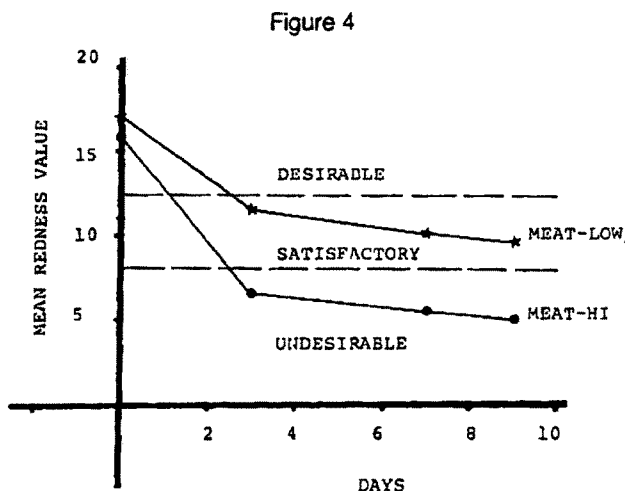
Frozen Meats

Frozen packaged meat has become more and more acceptable in the wholesale and institutional trade, but frozen retail cuts constitute only a small part of the market at present. The primary concern for the frozen storage of meat is the problem of freezer burn. This is caused by severe moisture loss from the surface layers. To prevent water vapor migration, void spaces in the frozen packages should be restricted and the temperature during the storage should be kept relatively constant. The meat should be in a skintight package as with a shrinkable film that has low permeation to oxygen, water vapor and volatile flavor components.

Another study was conducted with the same set-up as described in the experiment with fresh meat except the meats were frozen immediately after cutting, before packaging (Gilbert et al., 1981). The meats packaged with air were shown to have much brighter red color than in the vacuum packages. Vacuuming has significant (P<1% level) effect on the changes in loss of brightness (ΔL value) of frozen meat which indicated that the meat brightness is directly related to availability of oxygen to meat surface (Figures 5 and 6). On the other hand, there was evidence of light effects (P<5% level) on the color of the meat (Figure 7).
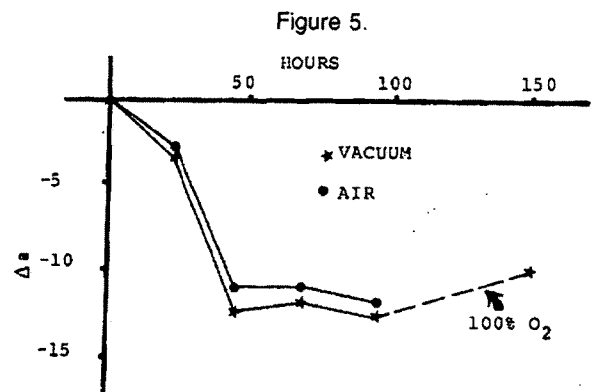
Figure 5.

Figure 5. Changes in mean Δa values of packaged frozen beef.

Figure 4

Figure 4. Redness changes of packaged fresh beef samples with different initial bacterial loads.

Figure 6.

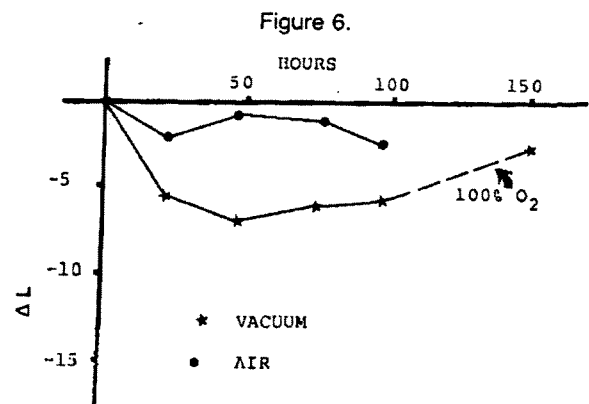

Figure 6. Changes in mean ΔL values of packaged frozen beef.
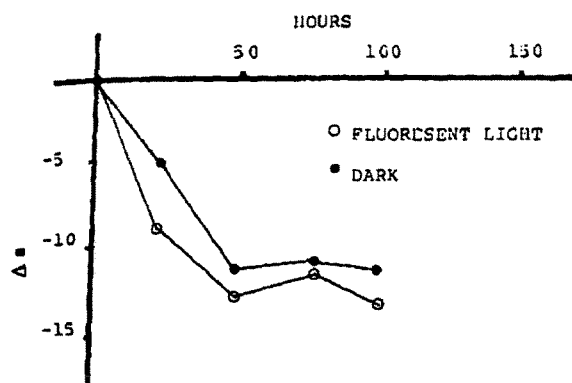
Figure 7

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Figure 7. Effect of light on changes of redness (Δa) of packaged frozen beef.

The vacuum packaged meats were opened after seven days of storage and exposed to 100% O_2. The changes in both a and L values were shown by the dotted line in Figures 5 and 6. These results demonstrated the reversibility of purplish red color to bright red color. However, the reversible process was not complete, probably due to some of the meat pigments being already in the oxidized stage (metmyoglobin).

Processed Meats

Processed meats, such as frankfurters and luncheon meats, should be protected from light and oxygen. A vacuum package with a film of relatively low oxygen and water vapor permeability can aid considerably in extending the product's shelf life.

Gilbert and Huang-Lai (1982) have studied the shelf life of ham packaged with cook-in films, a special packaging technique which combines shrink film, thermoforming and vacuum sealing. The product was filled in a pre-formed package before cooking, then sealed into a semi-rigid container. During the cooking cycle it shrinks around the product to assume the final taut configuration.

Fourteen lbs. size ham samples packaged in 9 different film materials supplied from Allied Fibers and Plastics (Morristown, NJ) were used to evaluate the product stability stored under 35°F in darkness. All of the films have good barrier properties (30 to 93cc/m²/24hr/atm for O_2 permeability). Sensory and microbiological qualities were determined after three months of storage, CO_2 concentration of fluid within packages was also measured. Good correlation was found between CO_2 concentration and aerobic bacteria count ($r = 0.8$). The bacterial load on packaged hams was within commercially acceptable levels. However, sensory qualities (surface color and aroma) were judged to be slightly less acceptable as compared with a reference sample of freshly packaged ham. It was found that the best product storage stability was related to the film that gave excellent shrinkage with tightly packed packages. Loose pockets of ham fluids within the packages are undesirable. These provided a media for the bacteria to grow and the liquid could also contribute to the pale faded surface appearance of the ham by washing off the color pigments.

Conclusion

Film permeability properties are of major importance to the shelf life of packaged meats. Theory of permeation and various factors that affect permeability have been presented to show the parameters of this aspect. The practical relations of permeation to quality of packaged meats were also examined. It is concluded that much of the literature concerning barrier requirements for fresh meat is not valid since the relation to microbial competition for oxygen was not considered. The oxygen demand by sterile fresh meat is quite low. Thus, most of the permeated oxygen is used in bacterial growth. Controlled atmosphere (high O_2 and CO_2 or low O_2) in relatively impermeable films storage provides one route to regulate both meat pigment and bacterial growth but this system requires close control of initial microflora, particularly with high initial oxygen level.

References

Barrer, R.M. 1951. "Diffusion In and Through Solids." Cambridge University Press, London.

Brody, A.L. 1970. Flexible packaging in foods. CRC Reviews in Food Tech. 1:71-155.

Carmen, P.C. 1956. "Flow of Gases Through Porous Media." Academic Press, London.

Crank, J. and Park, G.S. 1968. "Diffusion in Polymers." Academic Press, New York.

Daun, H. and Gilbert, S.G. 1974. Film permeation: The key to extending fresh produce shelf life. Packaging Engineering 19(8): 50-51, 53-54.

Daun, H. and Gilbert, S.G. 1979. How film choices affect shelf life of packaged meats. Packaging Engineering 24(4): 49-51.

Daun, H.; Solberg, M.; Franke, W. and Gilbert, S. 1971. Effect of oxygen-enriched atmospheres on storage quality of packaged fresh meat. J. Food Sci. 36:1011-1014.

Fox, J.B. 1966. The chemistry of meat pigments. J. Agric. Food Chem. 14:207.

Frisch, H.L. 1956. Gas permeation through membranes due to simultaneous diffusion and convection. J. Phys. Chem. 60:1177-1181.

Gilbert, S.G. 1981. Lecture notes on "Permeability measurement in relation to shelf stability of products."

Gilbert, S.G. and Daun, H. 1971. Unpublished data.

Gilbert, S.G.; Hatzidimitriu, E.; Lai, C.C. and Passy, N. 1983. Study of barrier properties of polymeric films to various organic aromatic vapors. Presented at the Third International Flavor Conference, Greece.

Gilbert, S.G. and Huang-Lai, G.R. 1982. Unpublished data.

Gilbert, S.G. and Hayakawa, K. 1975. Control of ripening and deterioration in packaged fresh produce. Singapore Polytechnical J. 7:33-36.

Gilbert, S.G. and Lai, C.C. 1982. Unpublished data.

Gilbert, S.G.; Tanaka, S. and Paik, S.W. 1981. Unpublished data.

Hall, C.W. 1973. Permeability of plastics. Modern Packaging. 46:53:57.

Henig, Y.S. and Gilbert, S.G. 1975. Computer analysis of variables affecting respiration and quality of produce packaged in polymeric films. J. Food Sci. 40:1033-1035.

Ingram, M. 1962. Microbiological principles in prepacking meats. J. Appl. Bact. 25:259-281.

Landrock, A.H. and Wallace, G.A. 1955. Discoloration of fresh red meat and its relationship to film oxygen permeability. Food Tech. 9:194-196.

Lebovits, A. 1966. Permeability of polymers to gases, vapors, and liquids. Modern Plastics 43:139-146, 150, 194-213.

54

Lieberman, E.R. and Gilbert, S.G. 1973. Gas permeation of collagen films as affected by cross-linkage, moisture and plasticizer content. J. Polymer Sci. Symposium Issue 41:33-43.

Long, F.A. and Thompson, L.J. 1954. Water induced acceleration of the diffusion of organic vapors in polymers. J. Polymer Sci. 14:321-327.

Meares, P. 1965. "Polymer Structure and Properties." Van Nostrand Reinhold Co., New York.

Mills, F. and Urbin, M.C. 1960. Packaging in "The Science of Meat and Meat Products" by American Meat Institute Foundation. W.H. Freeman and Company, San Francisco.

Newton, K.G. and Rigg, W.J. 1979. The effect of film permeability on the storage life and microbiology of vacuum packaged meat. J. Appl. Bact. 47:433-441.

Rikert, J.A.; Ball, C.O. and Stier, E.F. 1957. Factors affecting quality of prepackaged meat, II. Color studies. Food Tech. 11:520-525.

Rizvi, S.S.H. 1981. Requirements for foods packaged in polymeric films. CRC Reviews in Food Sci. and Nutr. 14:111-134.

Rogers, C.E. 1964. Permeability and chemical resistance in "Engineering Design for Plastics" edited by Baer, E. Van Nostrand Reinhold Co., New York.

Sacharow, S. and Griffin, R.C., Jr. 1970. Food Packaging. The Avi Publishing Co., Inc., Westport, Conn.

Talwar, R.; Gilbert, S.G. and Tibbetts, M.S. 1973. A technique to evaluate flavor retention by packaging materials for liquids. Presented at the 33rd annual IFT meeting, Miami.

Vieth, W.R. and Sladek, K.J. 1965. A model for diffusion in a glassy polymer. J. Colloid Sci. 20:1014-1033.

Yasuda, H. and Stannett, V. 1964. Barrier, Vapor in "Encyclopedia of Polymer Science and Technology." Vol. 2. Interscience Publishers, New York.